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INFLUENCE OF HUMIDITY UPON THE RESISTIVITY OF SOLID DIELECTRICS AND UPON THE DISSIPATION OF STATIC ELECTRICITY

BY

E. M. COHN AND P. G. GUEST

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UNITED STATES DEPARTMENT OF THE INTERIOR - BUREAU OF MINES

INFLUENCE OF HUMIDITY UPON THE RESISTIVITY OF SOLID DIELECTRICS AND UPON THE DISSIPATION OF STATIC ELECTRICITY[1]

By E. M. Cohn[2] and P. G. Guest[3]

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SUMMARY

The literature dealing with the electrical conductivity of solid dielectrics, including all its aspects and its relationships to other physical properties of these materials, is extensive and scattered in many books, pamphlets, and periodicals. It is believed that most of the important contributions to this field up to October 1943 have been listed and abstracted in this circular. Also included are some general references on static electricity. Methods of removing static charges are described; methods of and conditions for measurements of resistivity are discussed; equations for the calculation of resistivity are given; and methods of resistance measurements in situ are reviewed. Data on the variations of resistivity with changing conditions as well as explanations for them have been collected, and three tables showing the resistivity of various dielectrics at different humidities are included. The appendix contains a short development of the mathematical formulation of the charging and discharging currents due to interfacial polarization.

INTRODUCTION

Methods for Removing Static Electricity

Of the various means employed for preventing or removing accumulations of static electricity in industrial processes, grounding is the most common and most generally effective. It is a precaution readily applied to stationary machines and may often be utilized to good advantage to rid persons and portable equipment of an acquired charge. There are many situations, however, in which direct low-resistance grounding cannot be used, either because the charged bodies are insulators or are inaccessible, or because contact to a ground lead might give rise to a hazardous spark. If the charged body is a conductor, contact made to a neighboring conductor, even though the latter be insulated from ground and of relatively small capacitance, may also result in the occurrence of an incendive spark. In such instances, static electricity can sometimes be removed most satisfactorily by means of strong atmospheric ionization produced by radioactive material, X-rays, ultraviolet light, or A. C. high-voltage brush discharge. Where no danger exists from flammable

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materials, but where static is nevertheless troublesome, ionization produced by flames has been used with some success.

The most adaptable of all remedies for static electricity, other than grounding, and perhaps from all considerations the safest, is the employment of high atmospheric humidity. Humidification, like coating with conductive paint, is actually an indirect method of grounding, for it supplies moisture, which condenses upon the surfaces of nonconductors or insulators and converts them into high-resistance conductors. With very porous materials, it may penetrate deeply and result in internal conduction as well. Moisture does not appear to bestow any conductance to air however, for it is usually in the gas phase; if it is in the form of a mist or spray, the separate air-insulated particles actually tend to reduce the normal conductivity by entrapping the ions and rendering them less mo

Much general interest is being evidenced at the present time in static electricity control through air humidification as well as through the dir application of moisture to manufactured products. To estimate the deg of humidification required for effective and economical control, one sh know the extent to which moisture affects many kinds of dielectric ma terials and the reasons for the observed phenomena. The authors have reviewed numerous articles pertaining to dielectric measurements and have segregated here the information relating to the methods of and results from resistivity determinations on solid dielectrics.

Sources for General Information on Static Electricity

Some references on the general subject of static electricity are pre sented here for those readers concerned with the prevention of electro static disturbances, especially explosion hazards. A comprehensive survey of the history of electrostatic discoveries, the occurrence of static electricity, its hazards, and general provisions of controlling th phenomena has been compiled by Guest.4/ In a recent paper, Silsbee5 defines various electrical concepts, such as charge, potential, capaci ionization, and resistance. These definitions are followed by paragra on the nature and origin of static-electric charges in several industri processes, on the units of measurement and their quantitative relatio and on instruments and methods of measurement. A similar but some what more technical and detailed publication is that of Freytag,6/ whi

4/ Guest, P. G., Static Electricity in Nature and Industry: Bureau o Mines Bull. 368, 1933, 98 pp.

5/ Silsbee, F. B., Static Electricity: Nat. Bureau of Standards Circ. 438, 1942, 36 pp.

6/ Freytag, H., Raumexplosionen durch statische Elektrizität (Explo Hazards due to Static Electricity): Verlag Chem., G.m.b.H., B W35, 1938, 115 pp.

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f particular value for its extensive discussion of data on liquids, gases, l dusts. The hazards due to accumulation of static-electric charges in petroleum industry are the subject of an unpublished report by one of Fire Prevention Committees of the American Petroleum Institute.7/ fairly detailed description of the sources of electrostatic charge accu-lations in various industries and current methods of mitigation of the ards involved is given in a pamphlet published by the National Fire tection Association.8/

MEASUREMENT OF RESISTIVITY OF SOLID DIELECTRICS

Definitions

Volume Resistivity

On applying a voltage to a solid insulator (or dielectric), a current y pass across the surface as well as through the volume of the speci-n. The volume resistance of a material varies with the condition, e, and shape of the material, with the influence of the surrounding dium, and with the electrical potential used for the measurement. Al-ugh there are no rigid standards regarding the conditions of measure-nt, more or less quantitative comparison of the ease of current passage ough various substances can be made by referring to unit volume re-stances. The resistance between the two opposite faces of a centimeter e of an insulating substance is designated as volume resistivity, pro-ded the passage of electricity over the surfaces of the cube is infinitely all. Obviously, the volume resistivity, like the volume resistance, ries with the conditions of measurement.

Surface Resistivity and Total Resistivity

The surface resistance is subject to the same influences as the lume resistance. Again for the purpose of comparison, the surface sistivity is defined as the resistance between the two parallel edges a square centimeter on the plane surface of a substance, provided the ssage of electricity through the volume of the substance is infinitely all. The total resistance of a substance is the combination of its volume sistance and its surface resistance. This is called the total, leakage, insulation resistance. It is usually measured with both electrodes on same face, and the leakage resistance per centimeter separation of electrodes is the total, leakage, or insulation resistivity. This

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American Petroleum Institute Fire-Prevention Committees, Progress Report of Special Committee on Static and Stray Currents: Am. Petrol. Inst., 50 West 50th St., New York, February 1941, 16 pp.

Committee on Static Electricity, Nat. Fire Protection Assoc., 60 Batterymarch St., Boston, 1941, 50 pp.

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property is an indication of the ability of an object to dissipate static electricity.

Resistivity Measurement

Basic Unit

Specimen

Although in special cases, e.g., single fibers and tubular specimens it is necessary to adapt the measuring apparatus to the specimen, the usual procedure is to adapt the material under investigation to the apparatus. The sample holder consists of two metal surfaces, the electrodes, between which the substance is placed. The sample should be free of foreign materials, especially surface impurities, clean, and smooth, if possible. It should be in a convenient regular shape,9/ such as a square or round plate of uniform thickness, a cube, or a cylinder, so that the dimensions can be measured accurately for computing the resistivities. A close fit between the sample and the electrodes at all points is very desirable, as air spaces would require correction of the data.10/

Electrodes

The electrodes, of course, must also be clean and smooth and make good contact with the specimen. If solid metal is used, the pressure on the electrodes must be sufficient to insure good contact yet low enough to prevent deformation and undue compression of the sample. Hard-rubber disks covered with tinfoil and pressed to the specimen with a uniformly distributed pressure have been found to make better contact than solid metal. Because of the variation of the resistivity with small electrode diameters, the foil should cover at least 5 square centimeters11/ and be applied with a pressure of about 400 to 500 grams per square centimeter. The electrodes can be glued, sprayed, pressed, poured, or burned on to

9/ Curtis, H. L., and McPherson, A. T., Dielectric Constant, Power Factor, and Resistivity of Rubber and Gutta-Percha: Nat. Bureau of Standards Tech. Paper, 299, vol. 19, 1925, pp. 669-722.

10/ Pellat, H., Des diélectriques et de leur polarisation réelle. (On Dielectrics and Their Real Polarization): Jour. Phys., vol. 29, 3d ser. vol. 9, 1900, pp. 313-325.

11/ Kinzbrunner, C., The Testing of High-tension Insulating Materials: Electrician, vol. 55, 1905, pp. 809-812, 846-848.

12/ Appleyard, R., Contact with Dielectrics: Proc. Phys. Soc. London, vol. 19, 1905, pp. 724-739.

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ake good contact.[13] For rough measurements under ordinary humidity nditions, the effective number of contact points may be increased by pplying a thin coat of water containing soap or glycerin to the electrodes. hrader[14] found graphite coating best for samples with necessarily rough rfaces, as the graphite filled the surface irregularities. However, by r the most desirable electrodes for smooth surfaces are mercury elec- odes. They insure good contact with a minimum pressure, because they ssume the shape of the sample; hence, they are most widely used for ccurate measurements. The leads to the mercury are amalgamated pper tubes of known diameter.

For measuring surface and leakage resistivity, the electrodes are laced on the same face of the sample and usually 1 centimeter apart. nstead of one surface, two opposite surfaces can be used, with the positive nd negative electrodes of each face exactly opposite each other.

Conditions of Measurement

uard Ring

A guard electrode is used in electrical measurements to insure niform lines of force between the measuring electrodes and to eliminate rface leakage. Hence, it is of particular importance for volume-resis- vity determinations. Being at approximately the same potential as the arded electrode and surrounding it completely, the guard receives and ads away all the surface current coming from the unguarded electrode, us preventing erroneous meter readings. Usually, the guard ring is rounded, and the guarded electrode is connected to a grounded meter. reenfield[15] advises making the potential difference between guard and nguarded electrode somewhat greater than that between unguarded and arded electrodes and making the distance between guarded and guard ectrodes sufficiently large so that the insulation resistance between em is 100 to 1,000 times the ohmic resistance of the measuring circuit.

ielding

Although the guard electrode prevents the meter from registering ray surface currents in volume-resistivity measurements, the shield otects the circuit from stray foreign currents and from any ionizing

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[13] Vieweg, R. (editor), Elektrotechnische Isolierstoffe: Julius Springer, Berlin, 1937, 295 pp.

[14] Shrader, J. E., Conductivity of Insulating Material Near the Breakdown Voltage: Phys. Rev., 2d ser., vol. 17, 1921, pp. 502-507.

[15] Greenfield, E. W., Application of Guard Electrodes in Dielectric Measurements: Rev. Sci. Instr., vol. 13, November 1942, pp. 489-492.

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radiations that might otherwise enter the sample chamber, render the air abnormally conductive, and produce an apparent decrease in resistivity. Grounded metal plates or metal screens are used for this purpose. The latter may be partly or completely covered with metal foil. Another source of error in electrical measurements, polarization of the glass chamber in which the sample is kept, can also be avoided by the use of screens. It may be necessary to shield other components of the apparatus.

Humidity

As the variation of resistivity with humidity is the subject of another section, only the control of the humidity in the specimen container will be discussed here. Zero percent relative humidity obviously can be obtained by evacuating the chamber. In fact, this method is used for very accurate volume-resistivity determinations. Perfectly dry air which is confined within the test unit is a reasonably satisfactory substitute for vacuum. To control the relative humidity of the air in the measuring chamber, sulfuric acid with varying amounts of water is often used.16/ The relationship between the concentration and humidity is shown in figure 1. These humidities remain virtually constant within ordinary temperature limits. The humidity can also be regulated by using saturated salt solutions. To avoid corrosive action of acids or salts, one can use mixtures of known amounts of water and dry air, known volumes of dry and saturated air, or aqueous glycerin solutions.17/ The last are also almost independent of temperature between 0° and 70° C. However, the temperature and pressure prevailing during experiments must be recorded, as the resistivities vary with changes in these factors.

Voltage

From a fraction of one volt to several thousand volts have been used for insulation measurements. It has often been observed that the resistivity of solid dielectrics decreases as the applied voltage is increased, reaching a limit below which it will not fall until break-down voltage

16/ Wilson, R. E., Humidity Control by Means of Sulfuric Acid Solutions With Critical Compilation of Vapor-Pressure Data: Jour. Ind. Eng. Chem., vol. 13, 1921, pp. 326-331.
Jackson, V. H., and Mukerjee, A. T., The Utility of Desiccants in Electrostatic Measurements: Jour. Proc. Asiatic Soc. Bengal, new ser., vol. 16, 1920, pp. 1-11.

17/ Grover, D. W., and Nicol, J. M., The Vapour Pressure of Glycerin Solutions at 20°: Jour. Soc. Chem. Ind., Trans., vol. 59, 1940, pp. 175-177.

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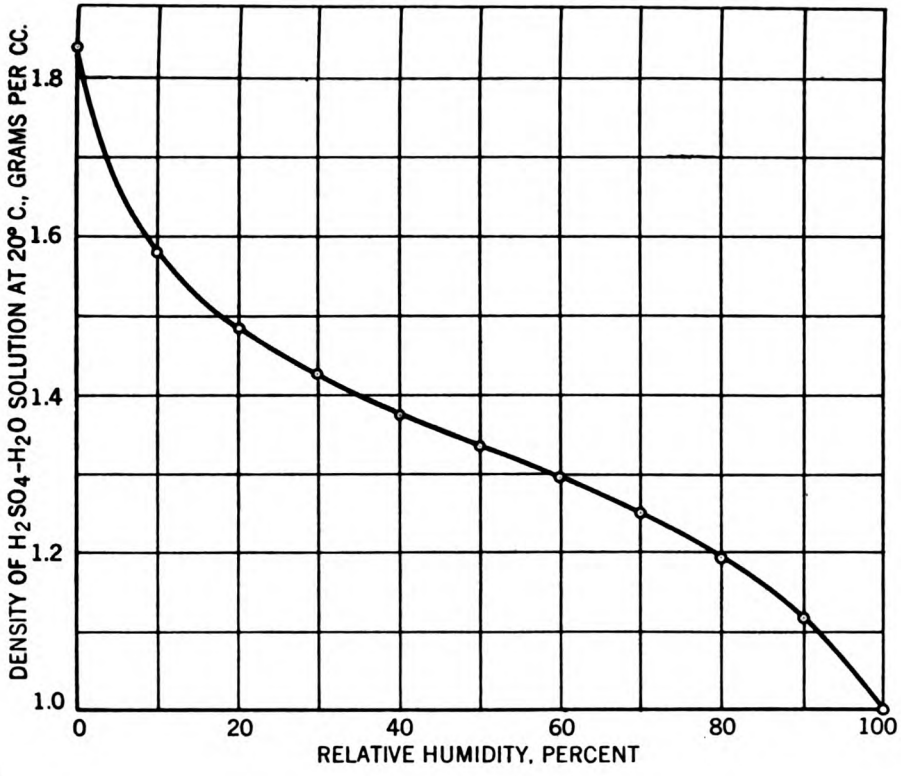

Figure 1.- Curve showing the relationship between density of a sulfuric acid solution and relative humidity that will be maintained by it in an enclosure.

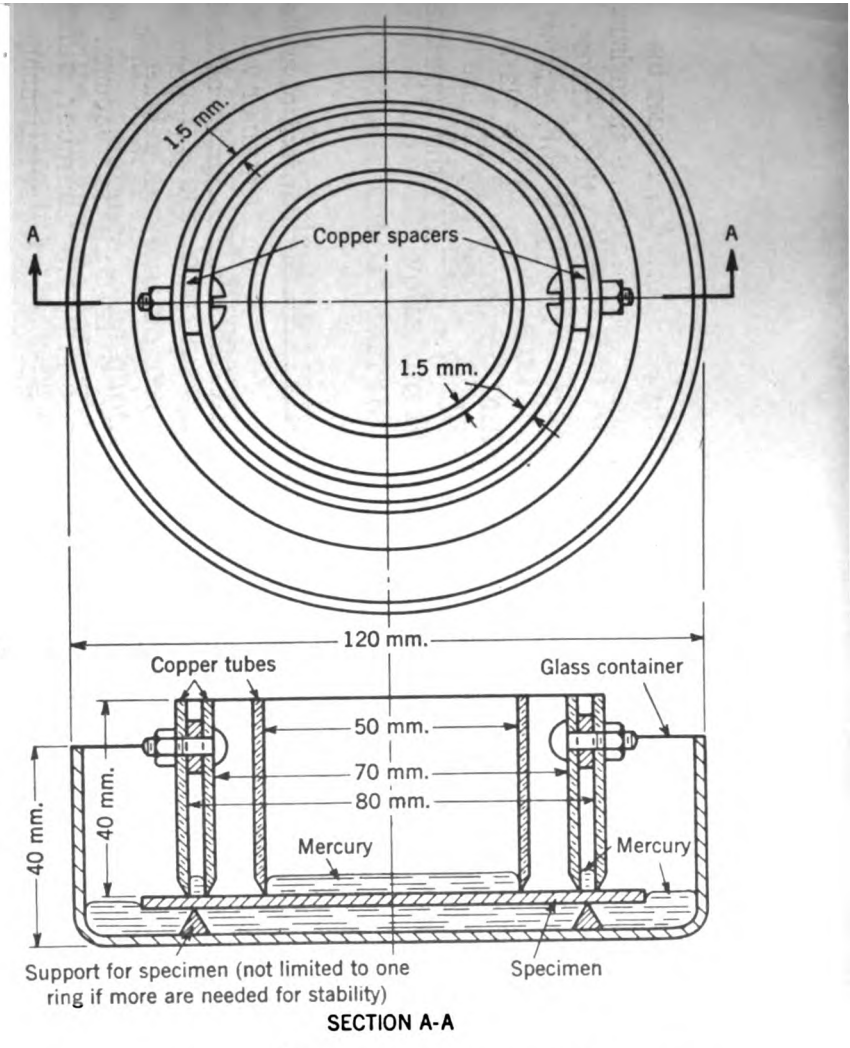

Figure 2.- Mercury electrodes for surface-resistivity and volume-resistivity tests on flat specimens.

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is approached. Kujirai and Akahira,[18] for example, found that the variation of resistivity of fibrous dielectrics becomes negligibly small above 200 volts. The usual test specifications call for 500 or 1,000 volts test potential to overcome this variation. Its cause must be sought in polarization phenomena, as Joffé[19] found Ohm's law to be valid from 0.1 volt/cm to 5 x 10^5 volts/cm for calcite, glass, and mica by considering only the instantaneous current.

Timing of Electrical Measurements

Charging and discharging of capacitors. - If the current passing through a dielectric upon application of an E.M.F. is measured immediately after voltage application and again at some later time, it will often be found that the resistance - the quotient of voltage and current - is much higher after the longer time interval. This phenomenon can be understood best by considering the charging and discharging of a capacitor.

A simple capacitor (such as the basic unit for resistance measurements) consists of two metallic plates separated by a nonconducting layer - the dielectric. In an ideal capacitor, the dielectric would be a perfect insulator; hence, no direct current could pass through it. Also, upon application of an electric field - assuming the current density to be sufficiently high - the ideal capacitor would be completely charged almost instantaneously; and when short-circuited, this capacitor would release the same amount of charge in the same short time interval, if no leakage to the surroundings had taken place.

Solid dielectrics deviate from the perfect example just described because their atoms and molecules are closely packed and exert considerable forces on each other. By reason of these forces and because of the difference in size, mass, and charge of the fundamental particles in the solid, it does not become completely polarized (or charged) at the time of application of the potential difference, but continues to absorb charge for some time; in some instances for hours or days. Murphy and Morgan[20]

18/ Kujirai, T., and Akahira, T., Effect of Humidity on the Electrical Resistance of Fibrous Insulating Materials: Inst. Phys. and Chem. Res., Tokyo, Sci. Papers, vol. 1, 1923, pp. 96-124.

19/ Joffé, A. F., The Physics of Crystals: McGraw-Hill, 1928, 198 pp.

20/ Murphy, E. J., and Morgan, S. O., The Dielectric Properties of Insulating Materials: Bell System Tech. Jour., vol. 16, 1937, pp. 493-512; vol. 17, 1938, pp. 640-669; vol. 18, 1939, pp. 502-537.

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enumerate the following four kinds of polarization, two of which are instantaneous (often called "normal") and two absorptive (or "viscous"):

1. Instantaneous polarization.

    a. Electronic - the displacement of electrons with respect to the nuclei of the atoms.
    b. Atomic - the displacement of atoms with respect to each other within the molecule, or of the lattice ions of opposite sign with respect to each other within ionized crystals.

2. Absorptive polarization.

    c. Dipole - the orientation in the applied field of molecules with permanent dipole moments.
    d. Ionic or interfacial - the movement of free ions through the dielectric.

Of these four types, the third is generally found to be of little importance in dry, solid dielectrics. On the other hand, water in or on the dielectric will show some dipole orientation.21/ Bragg 22/ explained these phenomena as follows:

21/ In recent years, the statistical method of absolute reaction rates 21a/, b/ has been used to investigate the ionic interfacial polarization. It substantiates further the statement that dipole rotation is of minor importance in solid dielectrics by showing that the heat of activation of viscous flow is smaller than the heat of activation of dipole rotation, or, in other words, that the bonds between neighboring molecules restrict the dipole rotation more strongly than the viscous flow.

21a/ Kauzmann, W., Dielectric Relaxation as a Chemical Rate Process: Rev. Modern Physics, vol. 14, 1942, pp. 12-44.

21b/ Powell, R. E., and Eyring, H., Frictional and Thermodynamic Properties of Large Molecules: Advances in Colloid Science, vol. 1, 1942, pp. 183-226; ed. E. O. Kraemer, Interscience Publishers, Inc., New York, 434 pp.

22/ Bragg, Sir Wm. H., The Molecular Structure of Dielectrics: Jour. Inst. Elec. Eng., vol. 77, 1935, pp. 737-748.

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When a charging potential is applied to a dielectric, the movement of the electrons relative to the nuclei to which they belong constitutes a true displacement current, which is reversible; but the movements of the ions constitute an ionic current, which may be long drawn out and may be only partly reversible.

When the applied potential is removed, the displacement charge disappears as quickly as it was aroused, if opportunity is given for it to do so; but the ions may take time to come back, if they come back at all, to their original position, urged to do so by the internal electric fields due to their own displacement. Again, there will be diversity of speed; some will get back quickly and others slowly. Hence, can arise the curious effect described as "charges coming out of a condenser in reverse order of that in which they were put in"***.

On the whole, it would seem safe to assume that the dipole effect in the solid must be far less than in the liquid. Moreover, one would expect any such effect to have a short "time of relaxation;" it would not drag on over long periods such as are found in the phenomena of "residual" charge and discharge. It would be more readily detected by high-frequency changes of potential comparable with infra-red frequencies. Residual charges and discharges are more likely to be due to ionic movement, which are known to be possible and to occur.

When the capacitor is disconnected from the source of the E.M.F. and the two electrodes are connected to each other, the discharge current flows in the opposite direction and takes a similar, often identical, course. In very pure dielectrics, such as amber[23] and sulfur,[24] the temporal course of the discharge is identical with that of the charging current. Leiste[23] found that the interfacial polarization current of amber varies

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23/ Leiste, E., Über die elektrische Oberflächenleitfähigkeit von Pressbernstein. (On the Electrical Surface Conductivity of Pressed Amber): Ztschr. Phys., vol. 62, 1930, pp. 646-672.

24/ Neumann, H., Leitfähigkeit und dielektrische Hysteresis einiger Isolatoren und ihre Beeinflussung durch Roentgen und γ- Strahlen. (Conductivity and Dielectric Hysteresis of Some Insulators and the Influence of X-rays and γ- rays on Them): Ztschr. Phys., vol. 45, 1927, pp. 717-748.

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with the magnitude of the applied voltage but is independent of the humidity. The discharge in silica glass 25/ is at first somewhat faster; later on, slightly slower than the charging current, but the total quantity of electricity is the same in both instances. In many dielectrics, particularly composite ones, 26/ not all of the electricity reappears on discharging; that is, some of the energy produces a permanent change in the dielectric or is dissipated as heat. 27/

Furthermore, solid dielectrics are not perfect insulators but permit the passage of electricity through their volume and over their surface. This current is generally ascribed to the movement of free ions rather than electrons. The volume conduction is usually due to the mobility of the smallest ion (e.g., Na in ordinary glass), and holes have actually been observed after prolonged electrolysis of rock salt, 28/ proving that Na ions have migrated to the cathode. The volume conduction of amber 29/ is constant with time and negligible compared with the surface conduction above 30 percent relative humidity. The surface conduction of amber is constant with time but variable with the humidity and with the applied voltage and is increased by dust and surface impurities. It is thus apparent that the current flowing in dielectrics has two components - the constant conduction current and the variable charging current. Hence, the resistivity varies with time, and the particular value obtained will depend on the method employed for its measurement. 30/

Measurement After Arbitrary Time Interval. - The practice of measuring the D.C. resistance of all solid dielectrics after the potential has been applied for the same time interval to each one seems to be the least satisfactory of the possible methods. One cannot be certain whether the resistance is the resistance of the material to the passage of electricity from one terminal to the other, or whether it is a combination of this and the resistance due to the state of polarization of the substance at that particular instant.

25/ Jaquerod, A., and Mugeli, H., Recherches sur les anomalies diélectriques du verre de silice. (Investigations of the Dielectric Anomalies of Silica Glass): Arch. Sci., ser. 5, vol. 4, 1922, pp. 10-26, 89-119.

26/ Whitehead, J. B., Lectures on Dielectric Theory and Insulation: McGraw-Hill Book Co., New York, 1927, 154 pp.

27/ A mathematical derivation of the expression for the interfacial polarization current will be found in the appendix.

28/ See reference 19.

29/ See reference 23.

30/ Strictly speaking, the conduction current need not always remain constant, as explained elsewhere.

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Measurement After Complete Polarization. - If the potential is applied until successive D.C. resistance measurements yield identical values, the body is completely polarized. Such conductivity values are important when the material is constantly under the influence of an electric field.

Measurement of Instantaneous Conductivity. - If a potential is suddenly applied to a dielectric that has been completely electrically "relaxed," that is, depolarized, the current used for polarization will be a maximum; hence, the apparent resistance will be least. For electrostatic surges, then, the instantaneous value of the D.C. resistance of dielectrics should be considered. By measuring the resistance at the moment of potential application to the "relaxed" specimen, four complicating factors are avoided:

1. Polarization effect.

2. Heating effect: During the flow of current, the temperature of the sample rises, bringing about a reduction of its moisture content if it is porous. Although increase in temperature usually lowers the resistance of dielectrics, desiccation tends to increase it. The two effects have different time constants and therefore produce a complex variation.

3. Electrolysis: Ions migrate toward the electrodes of opposite polarity.

4. Electrical endosmose: 31/

> The term electro-endosmose is applied to the phenomenon of the transfer of liquids through capillary tubes under the action of an electric field set up throughout the tubes and maintained at a given difference of potential***. Porous diaphragms***are treated merely as collections of fine capillaries.

Electrical endosmose is of importance only in very porous and fibrous substances.

Joffe 32/ mentions two other methods that can be used to measure the instantaneous D.C. conductivity of comparatively nonporous

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31/ Burton, E. F., Helmholtz Double Layer Related to Ions and Charged Particles: Coll. Symp. Mono., vol. IV, 1926, pp. 132-144.
32/ See reference 19.

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homogeneous materials. The first consists in measuring the change in current, $\triangle I$, with a sudden change in potential, $\triangle V$; the instantaneous resistance is $\triangle V/\triangle I$. The other method is the measurement of the opposing E.M.F. P (due to polarization) when the change of P with time is negligibly small; that is, when polarization is virtually complete. Then, the instantaneous resistance

$$R = \frac{V - P}{I}$$

Murphy and Morgan[33] have found that A.C. measurements can be used to determine the instantaneous conductivity. According to these authors, the A.C. conductivity increases as the frequency is increased and approaches a limiting value, "infinite-frequency conductivity," which is equal to the instantaneous D.C. conductivity. At "infinite frequency," there is obviously no opportunity for polarization in the dielectric. The advantages of this method are that it can be used for all kinds of dielectrics under all conditions of humidity, and that the time of measurement is not critical as long as the heating effect is negligible.

Other Conditions

Considering again the influence of the air in the test chamber, it is obvious that corrections must be made for the air conductivity if very accurate data are desired. For this purpose, the electrical resistance of the test unit is measured without a specimen.[34] Walter,[35] contrar to previous investigators, found the conductivity of an enclosed volume o air to be constant. Water vapor does not change the conductivity of air. The influence of CO_2 in the air on the conductivity of dielectrics seems to be very small.[36] Exposure to light, X-ray, and ultraviolet radiation often produces temporary or permanent changes of the resistivity of solids, the latter being due to chemical changes in the nonconductor. Thus, Curtis[36] found that a 20-hour exposure to ultraviolet light may not affect the surface resistivity at all or may lower it as much as 48,000 times (rubber), depending on the dielectric.

33/ See reference 20.

34/ See reference 23.

35/ Walter, B., Über die Zerstreuung der Elektrizität in einer abgesch senen Luftmenge. (On the Leakage of Electricity in an Enclosed Volume of Air): Ann. Phys., 5th ser., vol. 37, 1940, pp. 326-332; vol. 38, 1940, pp. 232-244.

36/ Curtis, H. L., Insulating Properties of Solid Dielectrics: Nat. Bure Standards Sci. Paper, vol. 11, No. S234, 1915, pp. 359-420.

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Contact with deleterious chemicals must be avoided, of course.[37] Immersion of rubber under water for long periods, for example, may cause formation of fine holes.[38] Previous mechanical or electrical treatment of the substance may alter its electrical properties. It is desirable, therefore, that the history of the sample be known, and that materials that are to be used under extraordinary conditions be tested during and after subjection to such conditions. In anisotropic substances, the resistance depends on the axis along which the measurements are made. Fe[39] states that the conductivity of quartz is "many thousands of times greater in the direction of the principal axis than in a direction perpendicular to this." Also, the polarity of the D. C. causes differences in resistance values at times. Although frequent reversal of the D. C. tends to equalize the values, it is advisable to use A. C. for such substances if an average value is desired (see, also, Timing of Electrical Measurements).

Moisture-conditioning of the specimens is very important because long hysteresis effects are frequently experienced [40], [41], [42], [43]. Various investigators have found it necessary to expose their samples for three days to several weeks to air containing the desired amount of moisture to make sure that the moisture content of the dielectrics was in equilibrium with that of the air. The samples should also be conditioned at the temperature of their surroundings, and the temperature should not vary excessively during measurements. The change of resistance with large temperature fluctuations may be very pronounced, and sizeable hysteresis effects have been observed[44].

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[37] Passavant, H., Bericht über die Arbeiten der Kommission für Isolierstoffe. (Report on the Work of the Committee for Insulating Materials): Elektrotechn. Ztschr., vol. 33, 1912, pp. 450-456.

[38] Curtis, H. L., and Scott, A. H. Change of Electrical Properties of Rubber and Gutta-Percha During Storage Under Water: Nat. Bureau Standards Jour. Research, vol. 5, No. RP213, 1930, pp. 539-552.

[39] See reference 19.

[40] Williams, R. R., and Murphy, E. J., The Predominating Influence of Moisture and Electrolytic Material Upon Textiles as Insulators: Bell System Tech. Jour., vol. 8, 1929, pp. 225-242.

[41] Bhattacharya, G. N., On the Volume and Surface Resistivities of Shellac Moulded Materials: Indian Jour. Phys., vol. 16, Pt. III, June 1942, pp. 147-154.

[42] See reference 18.

[43] Kujirai, T., Kobayashi, Y., and Toriyama, Y., Absorption of Moisture by Fibrous Insulating Materials: Sci. Papers, Inst. Phys. and Chem. Res., Tokyo, vol. 1, 1923, pp. 79-95.

[44] See reference 25.

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Specific Apparatus Used for Resistivity Measurements

Electrodes

Figure 2, taken from the British Standard Methods of Testing Vulcanised Rubber,[45] illustrates the typical mercury-electrode arrangement for flat specimens. Curtis[46] used essentially such an arrangement as well as metal-strip electrodes, which were wrapped with tinfoil to insure good contact. For tubular materials, he used wires spaced 1 centimeter apart and twisted tightly around the tube to measure surface resistivities. Curtis and McPherson[47] used flat, circular, specimen disks of rubber and gutta-percha with embedded, flat, circular electrodes of unequal diameters, one on each side of the disk, which were pressed into the materia Absolute centering of the electrodes was thus unnecessary. As such embedded electrodes do not adhere to certain rubber compositions, Curtis, McPherson, and Scott[48] removed the metal plates and painted the recessed areas with conducting lacquer. To measure the resistivities of amber, sulfur, and paraffin, Neumann[49] graphited the samples and used a pressed in aluminum ring along the edge as a guard electrode. For some tests, he filled an aluminum cylinder containing a loose-fitting piston (held axially true) with the molten material. After solidification, the previously prepared bottom was ground off until an annular gap was obtained. The circular center on the bottom then served as the guarded lead, the remainder of the bottom and the sidewalls as the guard, and the piston as the unguarded electrode. Leiste's[50] sample holder consisted of two circular, exactly centered, metal plates of equal diameter holding between them 36 amber columns spaced in 3 concentric circles. Only thoroughly cleaned and highly polished amber was used, as preliminary tests with rough and with ground samples had given unsatisfactory results. Gnann[51],[52] used a modification of this apparatus for his investigation of quartz.

45/ British Standards Institution, British Standard Methods of Testing Vulcanised Rubber: No. 903, June 1940, 74 pp.

46/ See reference 36.

47/ See reference 9.

48/ Curtis, H. L., McPherson, A. T., and Scott, A. H., Density and Electrical Properties of the System, Rubber-Sulphur: Nat. Bureau Standards Sci. Paper, vol. 22 No. S560, 1927, pp. 383-418.

49/ See reference 24.

50/ See reference 23.

51/ Gnann, W., Über die elektrisch Leitfähigkeit von amorphem Quarz. (On the Electrical Conductivity of Amorphous Quartz): Ztschr. Phys vol. 66, 1930, pp. 436-452.

52/ Gnann, W., Das Isolationsvermögen von Bernstein, Quarzglas und Schwefel in trockener und feuchter Luft. (The Insulation Properties of Amber, Quartz Glass, and Sulfur in Dry and Moist Air): Phys. Ztschr., vol. 36, 1935, pp. 222-230.

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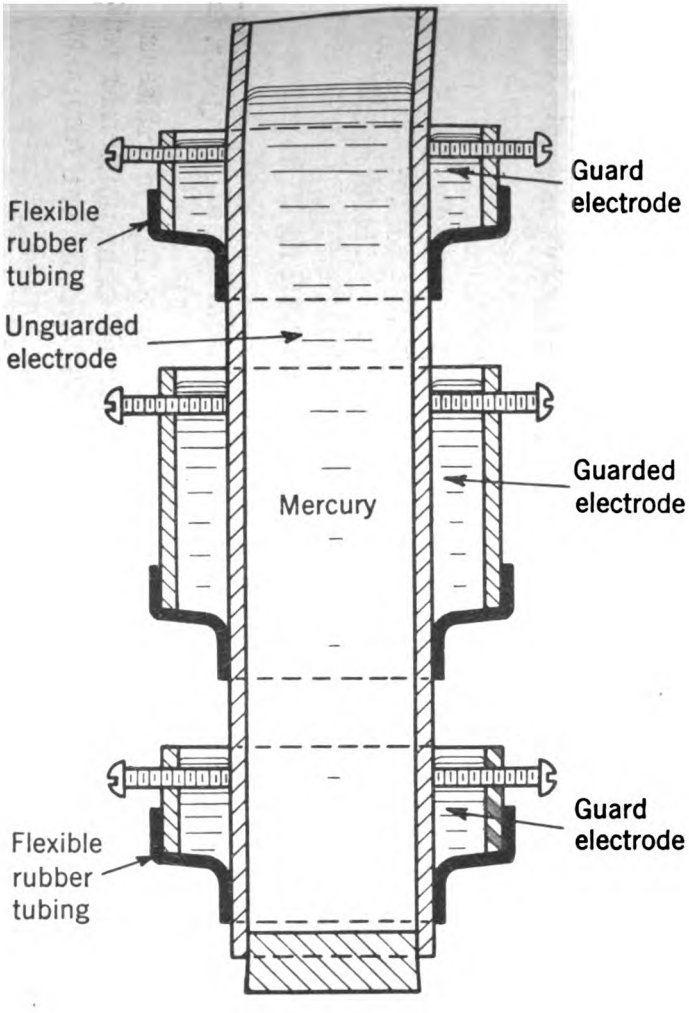

Figure 3.- Application of mercury electrodes to tubular specimens.

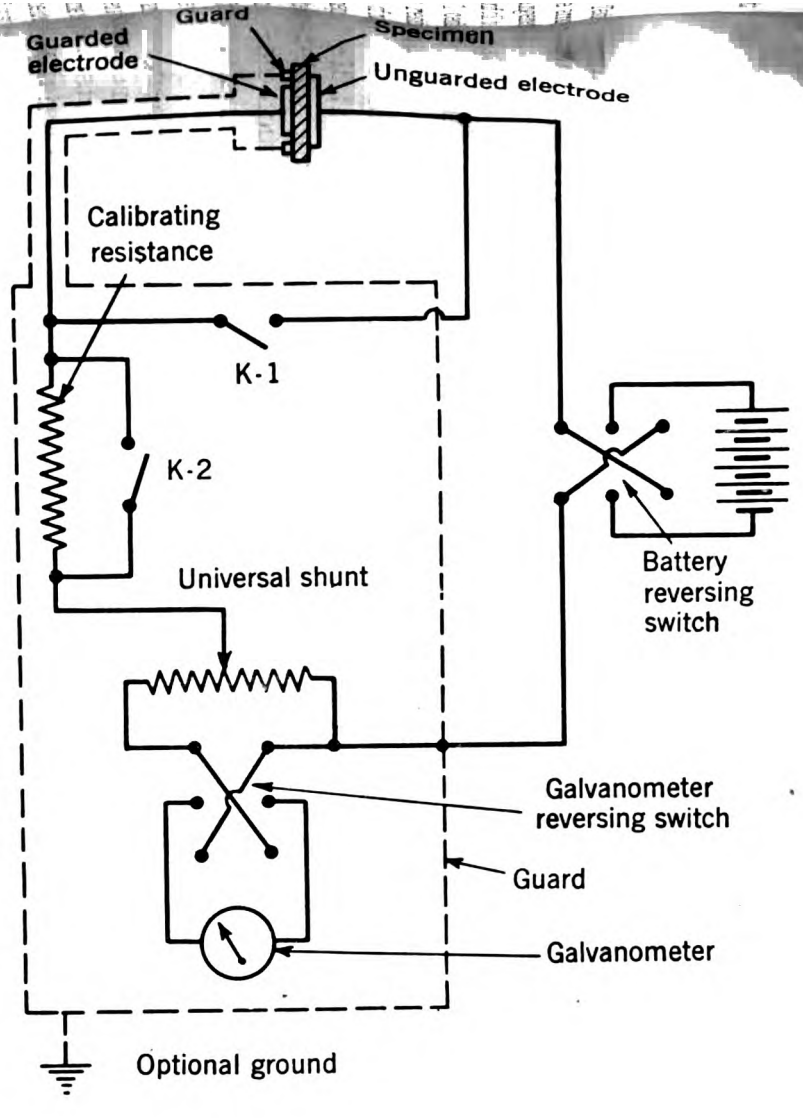

Figure 4.- Diagram of connections for determination of insulation resistance.

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Binding-post electrodes and strip electrodes for flat samples and tapered pin electrodes and mercury electrodes for tubular ones are described and illustrated in the 1939 Book of A.S.T.M. Standards, part 3[53]. The last are shown in figure 3. The mercury on the inside of the tube serves as the unguarded electrode, whereas the mercury-containing guarded electrode and the guard electrodes on each side of it are formed by amalgamated copper tubes of larger diameter than the specimen. They are held equidistant from the dielectric by set screws and closed on the bottom with flexible rubber tubing. Kujirai and Akahira[54] employed gold-plated brass cylinders, which were covered with the samples. Gold-plated brass nets were wrapped around these, which permitted the passage of moisture. For complete descriptions of these and other electrode systems, the reader should refer to the original articles cited in this paper.

Circuits

Various circuits, some very similar to each other, have been employed for resistivity measurements. Only a few of these are listed here, whereas many others can be found in the references cited throughout this circular. Pflier's[55] article describes a number of these and contains an extensive bibliography. Several investigators have used circuits employing so-called electrometer tubes as meters.[56], [57], [58], [59],

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53/ American Society for Testing Materials, Book of A.S.T.M. Standards: Pt. 3, No. D257-38, 1939, pp. 299-306.

54/ See reference 18.

55/ Pflier, P. M., Isolationsmessung mit Batterie und Gleichrichter. (Insulation Measurement with Battery and Rectifier.) Arch. Techn. Messen., No. 74, 1937, pp. T101-T102.

56/ See reference 41.

57/ Cherry, R. H., The Measurement of Direct Potentials Originating in Circuits of High Resistance: Trans. Electrochem. Soc., vol. 72, 1937, pp. 33-44.

58/ Müller, F., Electromotive Force Measurements With the Aid of Electron Tubes: Trans. Electrochem. Soc., vol. 62, 1932, pp. 335-343.

59/ Compton, K. G., and Haring, H. E., A Compensated Thermionic Electrometer: Ibid., 1932, pp. 345-357.

60/ Rose, G. M., A Method for Measuring Very High Values of Resistance: Rev. Sci. Instr., vol. 2, 1931, pp. 810-813.

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Other circuits can be found in the references below. 61/, 62/, 63/, 64/, 65/ A special circuit employing a Helmholtz pendulum to measure resistances after only 0.002 second of "electrification" was used by Scott, McPherson, and Curtis.66/ Silsbee67/ mentions another method of measuring resistances, which consists of charging the capacitor formed by the sample, the electrodes, and a static voltmeter to a known voltage and determining the time interval during which the voltage drops to another known value. Rehfisch68/ described an impulse circuit useful for determing the time of contact and the duration of voltage application. Figure 4 69/ illustrates the measuring circuit recommended by the A.S.T.M. It includes a switch for reversing the polarity of the current, a calibrating resistance, and an extensive guard system. Scott, McPherson, and Curtis70/ describe a chamber for measurements at temperatures ranging from -75° to 235°C., and Scott71/ used an apparatus in which pressure could be applied to tubular specimens during electrical measurements.

61/ Frost, A. A., Adsorption Potentials at Gas-Solid Interfaces: Electrochem. Soc., Preprint 82-10, 1942, pp. 109-113.

62/ Frost, A. A., and Hurka, V. R., Adsorption of Vapors at Solid Surfaces and the Change of Surface Electrical Potential: Jour. Am. Chem. Soc., vol. 62, 1940, pp. 3335-3340.

63/ Scott, A. H., and McPherson, A. T., Dielectric Constant, Power Factor, and Conductivity of the System Rubber-Calcium Carbonate: Nat. Bureau Standards Jour. Research, vol. 28, No. RP1457, 1942, pp. 279-296.

64/ Scott, A. H., McPherson, A. T., and Curtis, H. L., Effect of Temperature and Frequency on the Dielectric Constant, Power Factor, and Conductivity of Compounds of Purified Rubber and Sulfur: Nat. Bureau Standards Jour. Research, vol. 11, No. RP585, 1933, pp. 173

65/ General Radio Co., General Radio Experimenter (House Organ): vol. 14, No. 9, February 1940, pp. 3-7.

66/ See reference 64.

67/ See reference 5.

68/ Rehfisch, T. J., A Contact and Timing Indicator for Insulation Measurements: Jour. Sci. Instr., vol. 18, 1941, pp. 63-65.

69/ See reference 53.

70/ See reference 64.

71/ Scott, A. H., Effect of Pressure on the Dielectric Constant, Power Factor, and Conductivity of Rubber-Sulphur Compounds: Nat. Bureau Standards Jour. Research vol. 15, No. RP806, 1935, pp. 13-34.

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Calculation of Resistivity

The quantities measured must be such that from them the resistance and the dimensions of the capacitor formed by the sample and the electrodes are known. It may be assumed that the dimensions can be measured directly; the resistance, on the other hand, will sometimes have to be calculated from data that are more exact than resistance measurements could be under the circumstances.

Thus, Leiste[72] measured the capacitance, C, of his system in electrostatic units, the potential, E, in volts, and the time, t, in seconds. From these, he calculated the current,

$$I_{total} = \frac{CE}{9x10^{11}t} \text{ amps,} \qquad (1)$$

and the resistance,

$$R = \frac{E}{I_{total}} = \frac{9x10^{11}t}{C} \text{ ohms.} \qquad (2)$$

Having also determined the leakage of the apparatus due to the conductivity of the air, he could find the part of the resistance due to the sample alone:

$$R = E/(I_{total} - I_{air}), \qquad (3)$$

which, for measurements of ordinary accuracy, reduces to equation 2.

For the method of measuring resistance, as described by Silsbee,[73] the capacitance, C, initial and final voltages, E_1 and E_2, respectively, and the time interval, $(t_2 - t_1)$, must be known. The resistance is then

$$R = \frac{0.43\,(t_2 - t_1)}{C\,(\log_{10}E_1 - \log_{10}E_2)}, \qquad (4)$$

where R is in ohms for t in seconds and C in farads. In the special case, when $E_2 = 1/2\ E_1$,

$$R = 1.44\,(t_2 - t_1)/C. \qquad (5)$$

72/ See reference 23.
73/ See reference 5.

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Edge corrections for the capacitances of several capacitor systems lacking guard rings have been evaluted by Scott and Curtis.[74] Curtis,[75] who used a galvanometer and an electrometer in his investigation, computed the resistance in both instances by the same equation, viz

$$R = Et/Kd, \qquad (6)$$

where E is the applied potential, t the time interval, and d the deflection of the meter, K is either the ballistic constant of the galvanometer or the quantity of electricity necessary to produce unit deflection of the electrometer.

In the strictest sense, the only resistances that are measurable directly are the leakage resistance and the volume resistance, the former being measured on the surface and the latter (with guard ring) through the volume of the dielectric. The volume resistivity ρ is calculated from the volume resistance R_V, the area A of the guarded electrode, and the distance l between the electrodes, which is also the thickness of the specimen:

$$\rho = R_V A/l \text{ or } = EA/Il \qquad (7)$$

The surface resistivity is defined as

$$\sigma = R_S b/l \qquad (8)$$

where R_S is the surface resistance, b is the width, and l the length of the surface. As some current always flows through the body of the dielectric, the surface resistance can never be measured directly. In nonfibrous materials, however, it is essentially equal to the leakage resistance at high humidity when the volume resistance is very high in comparison. Conversely, the surface resistance of fibrous materials is comparatively high at high humidities, so that the volume resistance becomes virtually equal to the leakage resistance. Curtis[76] calculated that for electrodes spaced 1 cm apart on a test piece 1 cm thick, the effective contribution of the volume of the material to the leakage resistance is, roughly, three times the absolute value of ρ, the volume

74/ Scott, A. H., and Curtis, H. L., Edge Correction in the Determination of Dielectric Constants: Nat. Bureau Standards Jour. Research, vol. 22, No. RP1217, 1939, pp. 747-775.
75/ See reference 36.
76/ See reference 36.

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resistivity. As the leakages of electricity through the volume and over the surface are in parallel and constitute the total leakage r,

$$\frac{1}{|r|} = \frac{1}{\sigma} + \frac{1}{3|\varrho|} \qquad (9)$$

where $|r|$ and $|\varrho|$ are the values per unit distance and unit volume, respectively, expressed in ohms. It follows that

$$\sigma = \frac{3|\varrho||r|}{3|\varrho| - |r|} \qquad (10)$$

The surface resistivity of a nonfibrous substance is related to the volume resistivity ϱ' of the surface film,

$$\sigma = \varrho'/d \qquad (11)$$

where d is the thickness of the film.

The surface resistivity can also be calculated for surface measurements with circular binding-post electrodes on nonfibeous materials at high humidities.[77] If the posts have a radius c, and the distance between their centers is b, then, assuming the measured resistance R to be due only to surface leakage

$$\sigma = \frac{2\pi R}{\ln\left[\frac{b}{2c} + \sqrt{\left(\frac{b}{2c}\right)^2 - 1}\right]} \qquad (12)$$

where ln is the natural logarithm. If $4c > b > 3c$, then

$$\sigma \doteq \pi R \frac{b+c}{b-c} \qquad (13)$$

More equations for dielectric calculations, listed in convenient form, can be found in a paper by Greenfield.[78]

The leakage resistivity is the resistance per centimeter between two electrodes, each 1 square centimeter in area, placed on a sample 1 centimeter thick.[79]

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[77] See reference 53.
[78] Greenfield, E. W., Refresher for Dielectric Calculations: El. Eng., vol. 62, No. 10, October 1943, pp. 445-448.
[79] See reference 36.

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Resistance Measurements on Large Areas and Installations

Although the insulation characteristics of materials can be measured by laboratory experiments, and the behavior of dielectrics under various influences can thus be ascertained, it is sometimes impossible, or at least impracticable, to predict from such data the electrical behavior of large complex objects such as floors, table surfaces, and parts of machinery. The care and location of and the type of service and protection expected from combinations of dielectrics and conductors often make more or less rough tests in situ desirable. Much work of this kind has been done on electrical equipment such as motors and transformers; abundant descriptive material on the subject can be found in technical, especially electrical engineering, journals. Some interesting empirical conclusions based upon long-time insulation measurements have been summarized by the J. G. Biddle Co.80/ The "Megger" instruments used for these tests are quotient-type meters, which measure voltage and current simultaneously.

To determine the electrical leakage of large areas, two electrodes, such as described above, may be used. Measurements are made at different locations and with various electrode spacings. Such tests indicate the resistance of the surfaces proper. If the resistance of the surfaces to ground is to be measured, only one electrode is used, the other side of the circuit being connected to ground.

RESISTIVITY OF SOLID DIELECTRICS AT VARIOUS HUMIDITIES

Surface Resistivities of Nonfibrous Materials

The General Curve: Relative Humidity-Resistivity

At ordinary room temperatures, the surface of a dielectric exhibits a very high resistivity when completely desiccated; that is, only a small number of charged particles can travel along the surface. If such a dried dielectric is placed in an atmosphere of low relative humidity, it absorbs a certain amount of moisture. A nonfibrous substance will retain most of it on the surface. As the humidity is increased more and more moisture will be deposited on the surface, until eventually complete water paths extend from the positive to the negative electrode. As water is a much better conductor than a good dielectric, considerably

80/ Biddle, J. G. Co., Dielectric Absorption: Bull. 1660, June 1940.

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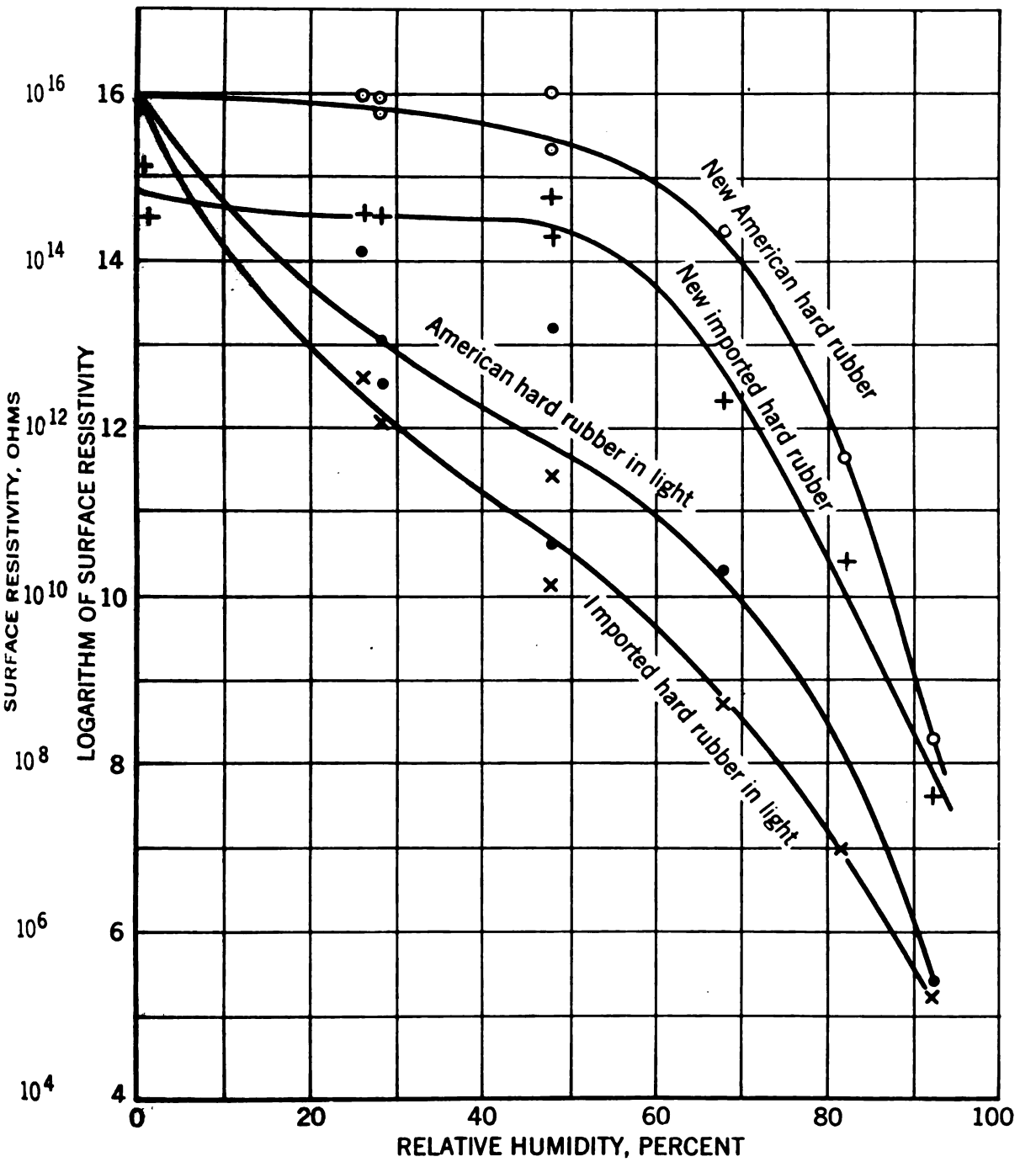

Figure 5.- Change of surface resistivity with humidity of samples of hard rubber before and after exposure to sunlight.

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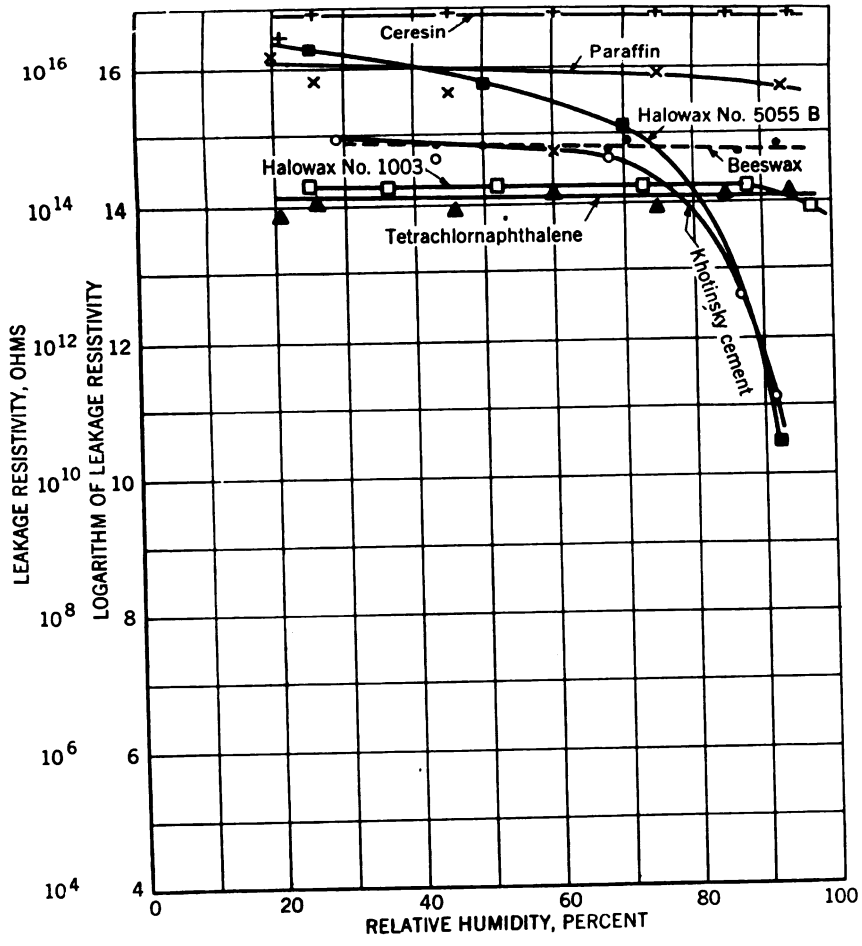

Figure 6.- Change of leakage resistivity with humidity of waxes.

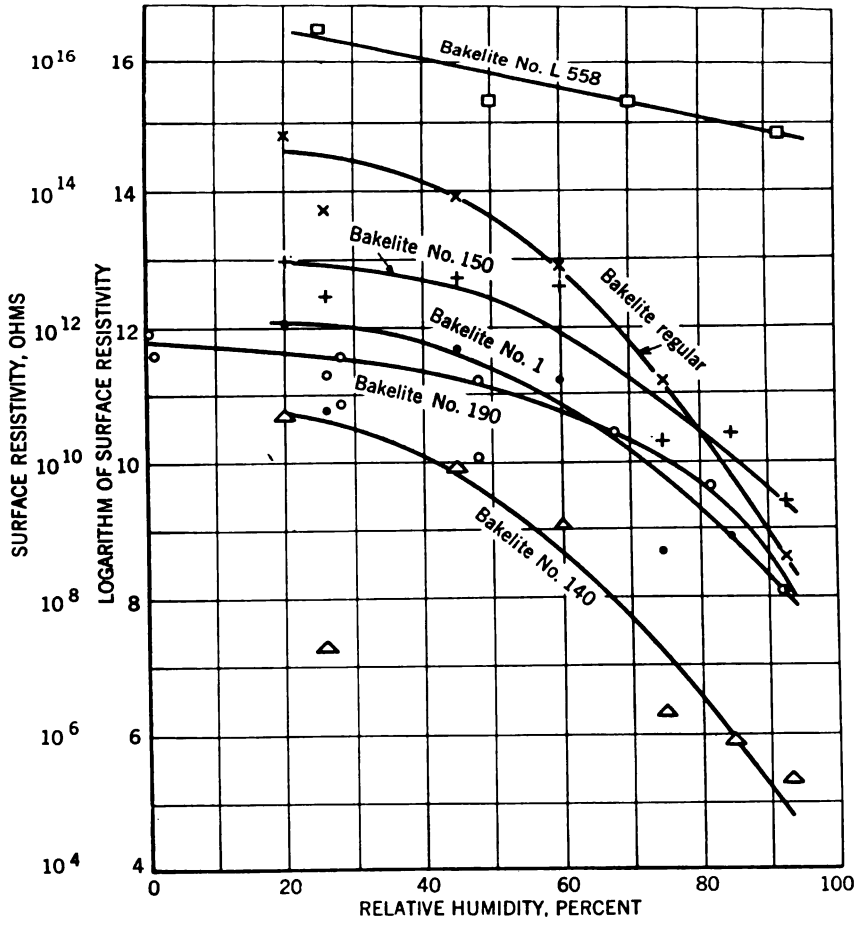

Figure 7.- Change of surface resistivity with humidity of bakelite.

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:ore electricity can pass along the deposited film than over the dry :urface of the insulator itself. The higher the humidity, the more :ater "bridges" are formed across the surface. Hence, the surface :esistivity falls, finally becoming so much smaller than the volume :esistivity as to obscure the latter almost completely. Anything that :ncreases the ion content of the water layer will further decrease the :esistivity. Water-soluble impurities on the surface of the dielectric r from the air, acid and alkaline gases in the air, and the molecules f the dielectric itself, if soluble in water or if dissolved by acidic r alkaline water solutions, can produce great changes in conductivity.

As very little water penetrates into the interior of a nonfibrous :onductor, the volume resistance varies comparatively little with :anges in the relative humidity. The surface resistance, however, is reatly affected by such changes. Figures 5, 6, and 7 were selected :om Curtis's 81/ paper to illustrate the curves obtained by plotting urface (or leakage) resistivity as a function of relative humidity. igure 5 contains the curves for hard rubber from two sources, each aving been measured when new and after long exposure to strong sunlight. he lowered conductivity is ascribed to the formation of soluble sulfates, hich were removed by immersing the sample in distilled water, thus estoring its insulating power.

The Exceptional Curve for Waxes

Figure 6 illustrates the exceptional behavior of waxes. They are mong the best insulators known, having a very high resistivity, which anges only slightly with relative humidity. This insensitivity to oisture is due to the fact that water does not spread over a wax sur- ce but collects in discrete droplets. For this reason, waxes are ten used as coating when high resistivity is desired. Care must be ken, however, that no cracks develop that would permit moisture to ep between the coating and the surface of the coated dielectric.82/

he Effect of Slight Changes in Composition and Conditions of Fabrication

Curtis's curves for Bakelite (fig. 7) provide a good illustration he large influence of small differences between samples. The only fference between Bakelite 140 and 150, for example, is that the first as condensed with caustic soda, the second with ammonia. Bakelite

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1/ See reference 36.

2/ Hou, C. H., Surface Conductivity of Ceresin-Coated Quartz: Rev. Sci. Inst., vol. 9, 1938, pp. 90-91.

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L558 is a very pure grade. Bhattacharya's[83] investigation of shellac-molded materials is further proof of this fluctuation: The volume resistivity of Kusum shellac at 0 percent relative humidity is 262×10^{13} ohm-cm., that of the molded substances ranges between 103×10^{13} and 16×10^{13} ohm-cm. At 90 percent relative humidity, the volume resistivity of the shellac is 80×10^{13} ohm-cm., that of the composite materials ranges between 8.2×10^{13} and 0.51×10^{13} ohm-cm. The surface resistivity values at any given humidity had a similar spread.

Natural products, such as rubber, mica, wood, and slate, have a wide range of resistivities owing to variations in composition. Plasticizers and products of pyrolysis,[84] as well as binders and fillers of synthetic plastics, can be just as effective for electrical conduction as water paths. Dellinger and Preston[85] measured surface and volume resistiviti of 15 grades of phenolic insulating materials using samples of different thicknesses for each grade. They found that the surface resistivity at 25 percent relative humidity varied between 130 percent and 11,000 percent, even within the same grade. Such discrepancies can be used (making due allowance for the unavoidable inaccuracies of measurement) as an indication of the degree of purity and uniformity of a product. The leakage resistance of the system Buna S-Gilsonite, which is of the order of 10^{15} ohms-cm., is virtually unaffected by water absorption.[86] Some of the more recent plastics are said to be excellent insulators, even at high humidities, but the authors have not been able to find any accurate data on the surface resistivities of these plastics. Twenty-four hours' immersion in water and 4 days' exposure to 80 percent relative humidity did not lower the volume and surface resistivities of polystrene and plexigum below 10^{12} ohms.[87] Hartshorn, et al,[88] mention several surface resistivities of plastics ranging from 10^{11} ohms for celluloid to 10^{15} ohms for glyptal, but they do not indicate the conditions of measurement. The values may change considerably at high humidities

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83/ See reference 41.

84/ See reference 20.

85/ Dellinger, J. H., and Preston, J. L., Properties of Electrical Insulati Materials of the Laminated Phenol-Methylene Type: Nat. Bureau Standards Tech. Paper, vol. 16, No. 216, 1922, pp. 501-627.

86/ Selker, A. H., Scott, A. H., and McPherson, A. T., Electrical and Mechanical Properties of the System Buna S-Gilsonite: Nat. Burea Standards Jour. Research, vol. 31, No. 3, September 1943, pp. 141-161.

87/ See reference 13.

88/ Hartshorn, L., Megson, N. J. L., and Rushton, E., Plastics and Electrical Insulation: Jour. Inst. Elec. Eng., vol. 83, 1938, pp. 484 487; discussion, pp. 488-496.

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continuous surface water films are formed.[89] Kienle and Race[90] have found that the volume resistivity of the solution used in preparing alkyd resins increases with resin formation and suggest using "electrical measurements as a means of following resin formation and as a criterion for determining the end point of resin preparation."

Table 1 contains approximate values of surface resistivity as interpolated from the graphs for most of the substances investigated by Curtis[91] and the range of values of shellac and shellac molded materials measured by Bhattacharya.[92] Because of the reasons given earlier, absolute values obtained may differ from those found by other investigators, but the table shows clearly the general relationship and trend of the resistivities. Most of these materials exhibit the greatest sensitivity of surface resistivity to moisture between 50 and 70 percent relative humidity. Curtis also found that most of them had a maximum surface resistivity below 10^{16} ohms and attributed this to an oily layer on the surface. This was confirmed by subsequent investigations of mica (see below) and by the fact that other investigators obtained immeasurably high surface resistivities on various materials after meticulous cleaning and exposure of their samples to vacuum.

The Resistivity of Glass and Mica

Littleton and Morey[93], who discuss the electrical conductivity of glass in the second chapter of their book, have remarked that more is known about the electrical properties of glass than about those of any other dielectric. As glass is a nonfibrous dielectric, its electrical behavior may be taken as typical of this group.

Glass is a somewhat porous substance, as can be seen from Langmuir's[94] experiments on lamp bulbs. After drying them in a vacuum, he heated them to 200°C. and found that 200 cu. mm. of water vapor, 5 cu. mm. of carbon dioxide, and 2 cu. mm. of nitrogen (corrected for room temperature and pressure) were evolved. When the bulbs were

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89/ Dunton, A. R., and Caress, A., Plastics for Use in Electrical Engineering: Jour. Inst. Elec. Eng., vol. 79, 1936, pp. 463-482.
90/ Kienle, R. H., and Race, H. H., The Electrical, Chemical, and Physical Properties of Alkyd Resins: Trans. Electrochem. Soc., vol. 45, 1934, pp. 87-107.
91/ See reference 36.
92/ See reference 41.
93/ Littleton, J. T., and Morey, G. W., The Electrical Properties of Glass: John Wiley and Sons, Inc., New York., 1933, 184 pp.
94/ Langmuir, I., Tungsten Lamps of High Efficiency, Part I: Trans., Am. Inst. Elec. Eng., vol. 32, Pt. 2, 1913, pp. 1913-1933.

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TABLE 1. - Surface resistivities of various materials at different humidities in billions of ohms[a]

Material	Relative humidity, percent		
	30	60	90
Ceresin[b]	79,500,000	79,500,000	79,500,000
Sulfur	12,600,000	5,000,000	126,000
Paraffin[b]	10,000,000	7,950,000	5,000,000
Kusum shellac	6,000,000	1,800,000	730,000
New American hard rubber	5,000,000	795,000	1.00
7 shellac-molded materials	3,800,000-1,130,000	1,000,000-100,000	200,000-4,200
Sealing wax	3,160,000	1,000,000	79,500
Amberite	2.550,000	633,000	3,160
Amber	1,000,000	398,000	126
Fused quartz	1,000,000	25.2	.200
Cleaned fused quartz	1,000,000	159,000	1,590
Beeswax[b]	630,000	630,000	630,000
Rosin	630,000	398,000	200,000
Glass (average of 2)	79,500	3.16	.100
Glazed porcelain	50,000	126	.500
Unglazed porcelain	12,600	63	.0398
Mica (average of 4)	10,000	100	1.00
New American hard rubber, exposed to light	6,300	100	.00159
Average of paraffined mahogany, poplar, and maple	2,550	630	3.16
Marble (average of 3)	100	1.00	0.0159
Celluloid	79.5	31.6	1.26
Ivory	15.9	2.52	.0316
Slate	.159	.0500	.0100

a/ 1 U.S. billion = 10^9

b/ Leakage resistivity (surface resistivity too great to measure).

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ated to 500°C., the total amounts of water vapor and nitrogen more n doubled, whereas the carbon dioxide increased sixfold. Bush and nnell[95] stated that these gases affect radically the conductivities of ss and quartz and that atmospheric moisture penetrates glass at inary temperatures. Because of their relatively high ionic mobility, alies increase the volume conductivity of glass, whereas the oxides inc, magnesium, lead, barium, and calcium decrease the electrical nductivity[96] Seddon[97] ascribed the slow increase of the volume con- tivity of glass with time to changes within the structure of the glass - henomenon that should be especially noticeable in an undercooled liquid. ylor[98] showed that the several sizes of complex silicate ions in glass an account for the various rates of interfacial polarization. By applying otential and letting the glass insulation of resistance thermometers arize, the conduction of the glass at 350°C. can be kept very small.[99]

Geddes[100] investigated the variation of surface resistance of ss with time and found that a freshly broken surface shows no preciable leakage in clean, dry air and in clean water vapor. In inary room air, the resistance was very low at first, then increased pidly, and finally fell again to a value somewhat higher than that for e newly exposed surface. Macaulay[101], Carson[102], and Strachan[103] vestigated the same process for mica in vacuum, clean dry air, and

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95/ Bush, V., and Connell, L. H., The Effect of Absorbed Gas on the Conductivity of Glass: Jour., Franklin Inst., vol. 194, 1922, pp. 231-240.

96/ Jackson, W., A record of Recent Progress Towards the Correlation of the Chemical Composition, the Physical Constitution, and the Electrical Properties of Solid Dielectric Materials: Jour., Inst. Elec. Eng., vol. 79, 1936, pp. 565-576.

97/ Seddon, E., Slow Changes in Physical Properties of Glass: Soc. Glass Technol. Jour., vol. 22 (Trans.), 1938, pp. 268-308.

98/ Taylor, N. W., Elastic After-Effects and Dielectric Absorption in Glass: Jour. Appl. Phys., vol. 12, 1941, pp. 753-758.

99/ Hoge, H. J., Electrical Conduction in the Glass Insulation of Resistance Thermometers: Nat. Bureau Stand. Jour. Research, vol. 28, RP 1466, 1942, pp. 489-498.

100/ Geddes, S., The Conductivity of a Freshly Broken Glass Surface: Jour., Roy. Tech. College, Glasgow, vol. 3, 1936, pp. 551-558.

101/ Macaulay, J. M., Effects of Surface Layers on Mica Insulation: Jour., Roy. Tech. College, Glasgow, vol. 1, 1924-27, pp. 5-13.

102/ Macaulay, J. M., and Carson, D., Further Experiments on Mica Insulation: Jour., Roy. Tech. College, Glasgow, vol. 2, 1929-32, pp. 161-173.

103/ Strachan, J. G., The Ageing of a Mica Surface: Jour., Roy. Tech. College, Glasgow, vol. 3, 1933-1936, pp. 343-352.

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and clean air-free water vapor. Only in the last instance did Macaulay and Carson note a low resistance value of a freshly cleaved surface, and then only after the water-vapor pressure was 80 percent or more of the saturation value. On contaminated surfaces, noticeable leakage developed when the water-vapor pressure was as low as 10 percent of the saturation value. They also found that an old surface would again exhibit the properties of a new one after having been heated to 400°C. According to Strachan water treatment of the surface of mica accelerates the increase of the surface resistance; and increasing the size of the glass vessel containing the sample has the same effect. He concluded that the water entraps contamination of an oily character from the air and allows this "grease" to spread over the surface. When the surface is so covered, it behaves much like a wax-coated surface.

Smail, Brooksbank, and Thornton[104/] showed that the resistance of the moisture film on glazed surfaces is very sensitive to small changes in temperature, and that moisture film formation and changes on these surfaces follow logarithmic laws. Yager[105/] differentiated three stages of electrical-leakage increase on glass surfaces. The moisture film formation on the glass governs the change of leakage in the first stage. The solution of soluble constituents of the glass in the water permits greater conductivity in the second stage. The increase in film thickness necessary to maintain equilibrium between the solution and the atmosphere augments the leakage in the third stage. A smooth increase of leakage is produced by these three processes. Yager and Morgan[106/] had observed earlier that at low humidities the surface resistance of Pyrex reached a steady value in about 2 hours after exposure. This time for electrical equilibrium increased with increasing humidity. According to adsorption data, the first monomolecular film of water on Pyrex should be formed near 50 percent relative humidity; and at that humidity, the first measurable surface leakage was noted. At and above this humidity they could not obtain electrical equilibrium. They attributed this failure to the chemical action of the water on the glass, and the attendant ionization. Atmospheric impurities further speed the

104/ Smail, G. G., Brooksbank, R. J., and Thornton, W. M., The Electric Resistance of Moisture Films on Glaced Surfaces: Jour., Inst. El Eng., vol. 69, 1931, pp. 427-436.

105/ Yager, W. A., Electrical Leakage Over Glass Surfaces: Bell Lab. Record, vol. 12, 1933, pp. 40-44.

106/ Yager, W. A., and Morgan, S. O., Surface Leakage of Pyrex Glass: Jour. Phys. Chem., vol. 35, 1931, pp. 2026-2042.

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cumulation of ions in the surface film.[107] Finally, Morey[108] found at the moisture film on glass near the dew point has a thickness of several millionths of a centimeter. He was able to remove the moisture from the better glasses simply by exposing them to a dry atmosphere, but the inferior grades had to be heated to expel all the water.

The Resistivity of Fibrous Dielectrics

Both nonfibrous and fibrous dielectrics have high surface and volume resistivities in dry surroundings. When these substances are very dry, their volume resistivity is much lower than their surface resistivity. The surface resistivity of both kinds of nonconductors increases with increasing humidity. Although the leakage of electricity over the surface of nonfibrous materials becomes very noticeable at higher humidities, their volume leakage usually increases only slightly (if at all) and therefore is quite negligible at high humidities. Fibrous materials, however, absorb a considerable amount of water even at moderate humidities, and under such conditions their volume leakage is much higher than their surface leakage.

Fibrous materials, like other dielectrics, exhibit dielectric polarization currents[109],[110], but these become unnoticeable as the conduction increases. Above 80 percent relative humidity, electrolytic polarization effects are observed.[111] As Murphy[112] expressed it with respect to textiles:

> ***a textile material connecting two electrodes acts in many respects as an electrolytic cell in parallel with a condenser, and ***the electrolytic cell component is chiefly responsible for the observed characteristics of the textile except at low humidities***at humidities above 20 to 30 percent, the residual E.M.F. in cotton is caused by the products

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107/ Seddon, E., Mitchell, W. J., and Turner, W. E. S., A Study of the Electrical Resistance Under Varying Conditions of Some Glasses and Porcelains of Possible Utility for Commercial Insulators: Jour. Soc. Glass Tech., vol. 23, 1939, pp. 197-238.

108/ Morey, G. W., Glass as a Dielectric: Jour. Franklin Inst., vol. 219, 1935, pp. 315-330.

109/ Murphy, E. J., Electrical Conduction in Textiles, III: Jour. Phys. Chem., vol. 33, 1929, pp. 509-532.

110/ Baxter, S., Electrical Conduction of Textiles: Trans., Faraday Soc., vol. 39, July-August 1943, pp. 207-214.

111/ Murphy, E. J., and Walker, A. C., Electrical Conduction in Textiles, I: Jour. Phys. Chem., vol. 32, 1928, pp. 1761-1786.

112/ See reference 109.

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of the electrolysis of the aqueous solutions which it contains; at humidities lower than this, other factors may predominate.

New[113] distinguishes three types of conduction currents according to the mass of the charge-carrying particles:

(a) Electronic conduction (as in metals).
(b) Ionic conduction (as in electrolytes).
(c) Colloidal conduction (as in electrophoresis and electrical dust precipitation).

At relative humidities higher than about 20 percent, the distribution, quantity, and electrolyte content of the water contained in fibrous dielectrics largely determine their conductivity.[114] Hence, most investigators agree that the conduction of these substances at higher humidities is almost completely ionic[115], [116], [117] [118], [119]. However, Baxter[120] has recently voiced the opinion that conduction in moist wool is electronic and caused by impurity centers formed by adsorbed water molecules.

The true D. C. conduction current may change during measurement. This is due to electrochemical changes in the composition of the test specimen caused by the application of a potential difference,[121] endosmose (see above), and heat effects. The A. C. conductivity of cotton is greater than the D. C. conductivity at low humidities, but both virtually coincide above 80 to 85 percent relative humidity.[122]

113/ New, A. A., Textiles in the Electrical Industry: Jour. Soc. Dyers and Col., vol. 47, 1931, pp. 10-13.
114/ See reference 40.
115/ Evershed, S., The Characteristics of Insulation Resistance: Jour., I Elec. Eng., vol. 52, 1914, pp. 51-73; discussion, pp. 73-83, 154-16
116/ See reference 40.
117/ See reference 113.
118/ Williams, J. W., The Structure and Electrical Properties of Insulating Materials: Jour. Phys. Chem., vol. 36, 1932, pp. 437-4
119/ Marsh, M. C., and Earp, K., The Electrical Resistance of Wool Fibres: Trans., Faraday Soc., vol. 29, 1933, pp. 173-192; discussion, pp. 192-193.
120/ See reference 110.
121/ Murphy, E. J., D. C. Conduction in Dielectrics: Bell Laboratories Record, vol. 12, 1933, pp. 8-12.
122/ Murphy, E. J., Electrical Conduction in Textiles, II: Jour. Phys. Chem., vol. 33, 1929, pp. 200-215.

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Kujirai and Akahira[123] investigated the insulation resistance of number of fibrous dielectrics by taking them through a humidity cycle from 3.3 to 90.0 to 10.1 percent relative humidity. The results are shown in the condensed table 2.

Of the various fibrous dielectrics, textiles have been most intensively investigated. Much valuable information on textiles and on the engineering aspects of air-conditioning is contained in a handbook edited by Thompson.[124] Williams and Murphy[125] classified textiles according to their conductivity and origin:

1. Animal fibers.

   These are of protein nature and are characterized by high moisture content at ordinary humidities and by great electrical sensitivity to further increments of moisture, yet possess excellent insulating properties under usual atmospheric conditions.

2. Vegetable fibers.

   These are of cellulosic nature and are characterized by lesser moisture absorption and lesser electrical sensitivity to further increments of moisture, yet possess relatively poor insulating properties over the range of prevalent atmospheric conditions.

2a. Cellulose acetate.

   This absorbs little water and accordingly has excellent insulating properties under like conditions.

Although the physical and chemical properties of fibers cannot be discussed in detail here, it should be pointed out that, in general, capillary and colloidal phenomena determine the electrical behavior of fibers and fibrous matter. Thus, Urquhart[126] accounted for the absorption of water by cotton by assuming cotton to be an elastic gel. Peirce[127] developed a theory of water absorption by cotton cellulose, in which he postulated that the water associated with 1 hexose unit

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123/ See reference 18.
124/ Thompson, A. W. (editor), Air Conditioning in Textile Mills: Parks-Cramer Co., Fitchburg, 1925, 497 pp.
125/ See reference 40.
126/ Urquhart, A. R., The Mechanism of the Adsorption of Water by Cotton: Jour., Text. Inst., vol. 20, 1929, pp. T125-T132.
127/ Peirce, F. T. A Two-Phase Theory of the Absorption of Water by Cotton Cellulose: Jour., Text. Inst., vol. 20, 1929, pp. T133-T150.

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TABLE 2. - Variation of insulation resistance of fibrous materials with humidity

Relative humidity, Percent	Insulation resistance, in ohms					
	Calico	Empire cloth	Linen	Manila paper	Red rope paper	Leatheroid
3.3	3.06×10^{11}	3.75×10^{9}	1.83×10^{11}	2.17×10^{11}	1.33×10^{11}	3.94×10^{11}
28.3	1.86×10^{9}	3.08×10^{8}	8.24×10^{8}	8.70×10^{8}	3.33×10^{9}	2.34×10^{9}
61.2	6.84×10^{6}	1.61×10^{7}	3.28×10^{6}	2.14×10^{6}	8.92×10^{6}	5.44×10^{6}
90.0	1.05×10^{4}	1.72×10^{5}	3.10×10^{3}	3.29×10^{3}	4.60×10^{3}	3.72×10^{3}
61.9	2.86×10^{6}	1.74×10^{7}	1.10×10^{6}	8.00×10^{5}	2.13×10^{6}	1.21×10^{6}
30.8	1.57×10^{9}	5.72×10^{8}	6.93×10^{8}	4.52×10^{8}	1.23×10^{9}	8.82×10^{8}
10.1	8.30×10^{10}	3.38×10^{9}	3.07×10^{10}	4.48×10^{10}	4.61×10^{10}	5.92×10^{10}

Relative humidity, percent	Insulation resistance, in ohms				
	Pressboard	Filter paper	Silk	Muslin	Asbestos paper
3.3	5.50×10^{11}	4.12×10^{11}	4.58×10^{11}	8.27×10^{11}	-
28.3	3.35×10^{9}	2.58×10^{9}	5.00×10^{10}	2.97×10^{10}	-
61.2	9.81×10^{6}	5.24×10^{6}	5.12×10^{8}	4.05×10^{8}	-
90.0	2.54×10^{3}	4.13×10^{3}	7.88×10^{3}	1.33×10^{5}	1.23×10^{3}
61.9	1.67×10^{6}	3.66×10^{6}	9.84×10^{7}	6.52×10^{7}	9.62×10^{5}
30.8	8.42×10^{8}	2.30×10^{9}	1.76×10^{10}	1.51×10^{10}	7.22×10^{8}
10.1	6.35×10^{10}	2.44×10^{11}	3.03×10^{11}	4.60×10^{11}	1.40×10^{10}

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hibits mostly its physical properties, whereas the water held inter-
icellarly shows mostly chemical properties. Evershed[128] ascribed
e conductivity of fibrous insulators to a small part of the total water
ntent - namely, that fraction that is contained in the pores extending
roughout the sample. Their resistance, in turn, is governed by the
allest cross section of each, so that even in these continuous channels,
rt of the water is electrically inactive. Walker[129] explained the
nductivity of cotton by relating it to the surface distribution of moisture
thin the submicroscopic structure of the cotton hair. He found that
he moisture content necessary to form a monomolecular layer on all
ternal surfaces of the cotton hair appears to be slightly more that
ercent of the hair weight."

There seems to be no difference between the longitudinal and
ansverse resistivities of textiles.[130] However, the electrode
essure on samples of which the transverse resistivity is being
easured is critical; variation of the pressure from a fraction of
pound to 170 pounds changes the resistivity 15 to 16 times.[131]

The change in resistivity with varying voltage, humidity, and
mperature may be summarized as follows:

1. At constant temperature and over a wide range of humidities (that is, excepting extremely dry and extremely moist conditions), Evershed found that the resistivity of textiles is a reciprocal function of some power of the applied voltage, the power being characteristic of the fiber.[132] This change of resistance with voltage was also observed by other investigators, the cause usually being sought in endosmose and electrolytic phenomena. Marsh and Earp[133] and Baxter[134], however, who worked with

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8/ See reference 115.
9/ Walker, A. C., Moisture in Textiles: Bell System Tech. Jour., vol. 16, 1937, pp. 228-246.
0/ Denham, W. S., Hutton, E. A., and Lonsdale, T., Measurement of the Electrical Resistance of Yarns and Cloths. Variation in the Resistance of Silk with pH: Trans., Faraday Soc., vol. 31, Pt. 1, 1935, pp. 511-519.
1/ See reference 130.
2/ See reference 115.
3/ See reference 119.
4/ See reference 110.

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fibers rather than yarn, found that Ohm's law is obeyed by wool fibers within this humidity range.

2. At constant temperature and voltage and over a wide range of humidities, "the insulation resistance of a textile sample is determined by its moisture content in such a way that if the logarithm of the resistance is plotted against the logarithm of the moisture content, a straight line is obtained whose slope is independent of the form of the sample and of the amount of impurities contained in the textile but is characteristic of the kind of material tested, that is, whether silk, wool, or cotton."135/ The relationship of resistivity to relative humidity has been expressed as follows: 136/

$$R = Ae^{x},$$

where R is the resistance, A is a proportionality factor, and x is a function characteristic of the dielectric and related to the humidity. Washing of textiles reduces their conductivity;137/, 138/, 139/ this is due to the removal of electrolyte. Acetylation of cotton has the same effect.140/ According to Marsh and Earp, less than 1 percent of oil content does not influence the conductivity of wool fibers. They also demonstrated that steaming fibers under tension as well as stretching fibers increases the resistance because of physical changes in the fibers.

The large change of resistance with small variations of humidity was explained by Evershed on the basis of the formation (or rupture) of many capillary water paths, by O'Sullivan (during discussion of Marsh and Earp's paper) on the basis of change of the radii of the capillaries and changing viscosity of the electrolyte, and by Baxter on the basis of the change of the mean distance between adjacent adsorbed water molecules. The electrical sensitivity of textiles to small changes in moisture content has been utilized in an instrument that measures the moisture content by measuring the insulation resistance.

135/ See reference 111.
136/ See reference 110.
137/ See reference 40.
138/ See reference 119.
139/ Glenn, H. H., and Wood, E. B., Purified Textile Insulation for Telephone Central Office Wiring: Bell System Tech. Jour., vol. 8, 1929, pp. 243-256.
140/ Illingworth, J. W., The Electrical Properties of Fibers: Textile Recorder, Feb. 1943, pp. 39-43; March 1943, pp. 42-46; May, 1943, pp. 46-50.

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This method is claimed to be superior to others used for the same purpose.141/

3. The resistance of cotton decreases by about 8 percent per °C. rise in the neighborhood of 25°C.142/ Baxter found that the change of resistance of wool fibers with temperature obeys a law similar to that shown in 2., that is

$$R = Be^{y},$$

where B is a constant and y is a function of the temperature that is characteristic of the material and independent of the humidity above 5 percent regain.143/ He also investigated wool-methanol and glass fiber-water systems and found them to behave like the wool-water systems. Slight temperature changes under ordinary conditions, however, have little effect.144/

Slater145/ carried out some comparative experiments on cotton ers and found146/ that the conductivity of cotton is over one thousand es greater at 60 percent relative humidity than at 20 percent, alough the moisture content rises only about 5 percent. Murphy and lker147/ state that the conductivity of cotton is 10^{12} times greater 99 percent than at 1 percent relative humidity and is an exponential ction of humidity between 20 and 80 percent. Denham and others148/ port that the conductivity of silk increases tenfold when the relative midity is raised from 75 to 80 percent. Marsh and Earp give a table hich is shown here) of typical values of the variation of the resistivity th humidity:

/ See reference 140.
/ See reference 111.
/ Regain is the ratio (expressed in percent) of the weight of the water content of a textile to the weight of the dry textile.
/ See reference 140.
/ Slater, F. P. , A Sensitive Method for Observing Changes of Electrical Conductivity in Single Hygroscopic Fibres: Proc., Roy. Soc., London, vol. 93B, 1924, pp. 181-193.
/ Slater, F. P., The Application of An Electrical Method to the Study of Moisture Absorption in Cotton and Its Bearing on Electrification in Cotton: Jour., Textile Inst., vol. 16, 1925, pp. 53-60.
/ See reference 111.
/ See reference 130.

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TABLE 3. - Total resistivity of wool fibers at various humidities

Relative humidity, percent	Moisture regain, percent	Resistivity, ohm-cm
53	12	1.6×10^9
63	14	1.5×10^8
71	16	2.3×10^7
79	18	6.0×10^6
83	20	2.5×10^6
86	22	1.3×10^6

APPENDIX

Mathematical Formulation of Residual Charge

Several summaries of the various quantitative explanations of anomalous or residual charge within the volume of solid dielectrics have appeared 149/, 150/, 151/, 152/, 153/. The best-known of these theories are those of Maxwell and Pellat. Curtis 154/ found the original Maxwell interpretation unsatisfactory as applied to mica capacitors. Grover 155/ and others used von Schweidler's 156/ modification of Pellat's theory with success. However, both Hartshorn and Whitehead showed that a similar extension of Maxwell's theory makes it as applicable to the phenomena observed in solid dielectrics as the Pellat-Schweidler theory. A short development of that part of the latter theory that concerns itself with D. C. phenomena is given here.

149/ Hartshorn, L., A Critical Résumé of Recent Work on Dielectrics: Jour., Inst. Elec. Eng., vol. 64, 1926, pp. 1152-1190.

150/ Whitehead, J. B., Dielectric Absorption and Theories of Dielectric Behavior: Trans., Am. Inst. Elec. Eng., vol. 45, 1926, pp. 102-1

151/ Curtis, H. L., The Electrical Resistivity of Insulating Materials: Trans., Am. Inst. Elec. Eng., vol. 46, 1927, pp. 1039-1048.

152/ See reference 21a.

153/ Meyer, U., Zur Theorie der dielektrischen Nachwirkung. (On the Theory of Dielectric Aftereffect.): Verh. deut. phys. Gesell., vol 19, 1917, pp. 139-154.

154/ Curtis, H. L., Mica Condensers as Standards of Capacity: Nat. Bureau Standards Bull., vol. 6, 1909-10, pp. 431-488.

155/ Grover, F. W., The Capacity and Phase Difference of Paraffined Paper Condensers as Functions of Temperature and Frequency: Nat. Bureau Standards Bull., vol. 7, 1911, pp. 495-578.

156/ von Schweidler, E., Studien über die Anomalien im Verhalten der Dielektrika. (Studies on the Anomalous Behavior of Dielectrics. Ann. Phys., vol. 24, 1907, pp. 711-770.

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o assumption regarding the physical mechanism of polarization of the lelectric need be made, but it is assumed that the "variable part of e polarization tends to a final value, which is proportional to the plied electric force, and that its rate of change is always proportional to s difference from its final value."157/

The following symbols are used in the equations:

A - area of the dielectric test plate.
B - constant = ahCDE.
C - capacitance.
D - dielectric constant.
E - voltage.
$\mathcal{E}$ - field intensity.
I - current.
J - electrical displacement.
K - proportionality constant.
T - definite time interval.
a - constant = reciprocal of the relaxation time of the viscous electrical displacement.
d - thickness of test plate.
h - constant, characteristic of the dielectric, identical with von Schweidler's ε and equal to J'/J. Pellat's h corresponds to hD here.
k - constant.
n - number of rates of ionic (viscous) displacement.
t - time.
y - anomalous current per unit area.

Subscripts are used for quantities having identical dimensions r example: y_1 - anomalous charging current; y_2 - anomalous scharging current). "Normal displacement" (Pellat's "imaginary larization") is von Schweidler's term for the electronic instantaneous larization; "viscous displacement" (Pellat's "real polarization") is s term for the anomalous ionic polarization, which varies with time. le following considerations apply to a capacitor with plane and para- l faces, which contains a homogeneous dielectric substance. The gth and width of the plates and specimen are very large, compared h the distance between the plates, so that the field is directly normal the plates and there are no air spaces between the plates and the electric.

When a constant voltage, E_o, is applied to this capacitor, the field ensity is constant and the total electrical displacement, J, at any time,

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7/ See reference 26.

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t, consists of two parts - the normal, largely electronic, displacement, J_o; and the viscous, largely ionic, displacement, J'. At the time, t., when the voltage is applied to the electrically "relaxed," that is, depolarized, specimen, only the normal displacemnet occurs:

$$J = J_o = D\mathcal{E}_o \qquad \text{when } t = 0. \tag{1}$$

The viscous displacement increases from zero at the time t = 0 to J'_∞ at the time $t = \infty$:

$$J'_\infty = hD\mathcal{E}_o. \tag{2}$$

The rate of change of J'with time is assumed to be

$$dJ'/dt = a\,(J'_\infty - J'). \tag{3}$$

The total viscous displacement at any time can therefore be found by integrating the last equation; since the limiting condition is J'=0 for t=0, the integration constant is equal to J'_∞ and the viscous displacement

$$J' = J'_\infty(1-e^{-at}) = hD\mathcal{E}_o(1-e^{-at}). \tag{4}$$

Obviously, the total displacement at any time is the sum of the normal and the viscous displacements:

$$J = J_o + J' = D\mathcal{E}_o + (1-e^{-at})\,hD\mathcal{E}_o. \tag{5}$$

After the voltage has been applied for an infinite time, the total dis - placement consists of the sum of the normal and the complete viscous displacements, which is also equivalent to the sum of the first two equations:

$$J_\infty = J_o + J'_\infty = (1+h)\,D\mathcal{E}_o. \tag{6}$$

(To avoid confusion, it is well to remember that Pellat's J_∞ is actually J'_∞) The rate of change of the total electrical displacement with time is equal to the rate of change of the viscous displacement with time, as the norma displacement is constant. It can therefore be found by differentiating either (4) or (5) with respect to time and is

$$dJ/dt = DJ'/dt = ahD\mathcal{E}_o e^{-at}. \tag{7}$$

The abnormal charging current per unit area of the capacitor is calculate from (7)

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$$y_1=\frac{1}{4\pi}\frac{dJ'}{dt}=\frac{ahD\xi_o}{4\pi}e^{-at} \qquad (8)$$

'or a dielectric of area A and thickness d, the total abnormal charging urrent is

$$I_1=\frac{A}{4\pi}\frac{dJ'}{dt}=\frac{DA}{4\pi d}ahd\xi_o e^{-at}; \qquad (9)$$

nd since $E_o = d\xi_o$ and $C = DA/4\pi d$,

$$I_1=ahCE_o e^{-at}=Be^{-at}. \qquad (10)$$

he above expressions were derived with the assumption that there is ly one rate of viscous displacement; that is, that all the ions in the electric are displaced at the same rate. Actually, different charged its and aggregates move at different velocities within the dielectric. o bring the equations in accord with experimental results, von Schweidler odified the equations by assuming a number, n, of rates of viscous dis- acements. The expressions are then

$$J=D\xi_o+\Sigma(1-e^{-a_n t})h_n D\xi_o, \qquad (5A)$$

nd $$I_1=CE_o\Sigma a_n h_n e^{-a_n t}. \qquad (10A)$$

he last is equivalent to

$$I_1=B_1e^{-a_1 t}+B_2e^{-a_2 t}\ldots+B_n e^{-a_n t} \qquad (10B)$$

ften approximated as $=Kt^{-k}$); that is, the sum of one, two, or more e functions. The last two equations correspond to actual phenomena. Jaquerod d Capt,158/ for example, found that the abnormal charging current of drogen-saturated silica glass can be expressed by $I_1=B_1e^{-a_1 t}$, and that

helium-saturated silica glass by $I_1=B_1e^{-a_1 t}+B_2e^{-a_2 t}$. a_1 is virtually same in both cases. With hydrogen, the current disappears after about minutes; with helium, it is less intense and lasts about 60 minutes. They sume ionization of the dissolved gas and ascribe the short-lived current to

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8/ Jaquerod, A., and Capt, C., Conductibilité électrique d'un verre de quartz. (Electrical Conductivity of a Quartz Glass.): Arch. Sci., vol. 42, 1916, pp. 328-330.

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electronic movement and the long-lasting current to ionic movement. Voglis159/ reported that for short time intervals (0.01 to 1 second), the approximation of equation 10B is, for some dielectrics, better expressed by

$$I_1 = K (t + T_1)^{-k},$$

where T_1 is a constant with the dimensions of time.

If one assumes complete reversibility of the anomalous charge and an identical temporal course (which need not necessarily be the case), the total anomalous discharging current at a time, t, after the voltage is disconnected is the same as the total anomalous charging current at a time, t, after the start of the charging operation, provided the sample had been completely polarized before the discharge began. Thus

$$I_2 = -I_1 \qquad (11)$$

But if the discharge begins after a definite charging interval, T, the total anomalous discharging current at any time, t, after the start of depolarization is

$$I_2 = -B (1-e^{-aT}) e^{-at} \qquad (12)$$

This, again, can be brought into accord with actual phenomena by taking the sum of one or more e functions:

$$I_2 = -[B_1(1-e^{-a_1T})e^{-a_1t} + B_2(1-e^{-a_2T})e^{-a_2t} + \ldots] \qquad (12A)$$

CONCLUSION

The resistivity of a dielectric determines its ability to dissipate accumulations of electricity by conduction; and, in general, when the rate of discharge is equal to or greater than the rate of charging, troublesome electrostatic phenomena are avoided. Hence, if dielectrics are employed in a location or process where generation of an electrostatic charge occurs and is undesirable or hazardous, they should be chosen so as to have sufficient conductivity under the given conditions. The method of resistivity measurement determines to some extent the values obtained. Hence, it is important to choose the correct

159/ Voglis, G. M., Über die dielektrischen Nachwirkungserscheinungen in festen Nichtleitern. (On the Dielectric After-effects in Solid Nonconductors.): Ztschr. Phys., vol. 109, 1938, pp. 52-79.

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pretreatment of the sample, electrode area, and pressure on the sample; voltage, temperature, and relative humidity; to insure equilibrium of the sample with its surroundings; and to measure the resistance (or its equivalent) after a suitable interval of "electrification." Unless very elaborate precautions are taken, the data will not be too accurate. However, extreme accuracy is not necessary for practical purposes, as provisions for a safety factor for the behavior of nonconductors in practice must be made anyway.

The data collected here show that the electrical leakage of most nonfibrous dielectrics becomes very noticeable around 60 percent relative humidity; the resistivity of fibrous materials decreases much faster and at lower humidities. Waxes are exceptionally good insulators, even at high humidity, because they are not wetted. Some of the newer plastics and synthetic rubbers are claimed to be as good as or superior to wax insulation. But, while their volume resistivity is high, even after immersion in water, too little is known about their surface resistivities at present to make any definite statements about their total resistivities at high humidities. From 22 letters received from manufacturers and testing laboratories in answer to inquiries, it is apparent that virtually no definite information on the variation of the surface resistivity of these materials with humidity is available, and that conflicting opinions as to their behavior exist. Because of the electrostatic hazards existing in industry, it would seem desirable that this property of the more recent dielectrics be more accurately evaluated.

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